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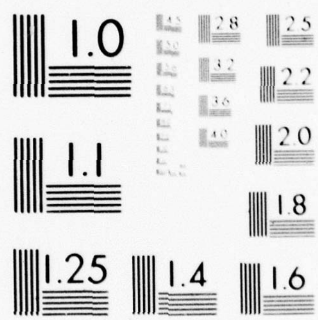

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TECHNICAL REPORT ARLCD-TR-77033

INITIAL PHASE IN THE DEVELOPMENT OF AN AUTOMATIC, OPTICAL SCATTER INSPECTION STATION

EDWARD G. KESSLER

DECEMBER 1977

U.S. ARMY ARRADCOM

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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18. SUPPLEMENTARY NOTES

This project has been accomplished as part of the US Army Materials Testing Technology Program, which has for its objective the development of laser scatter techniques for use as a tool for automated, non-contact surface inspection.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

optics	automation
optical inspection	munitions
lasers	quality control
defect detection	non-destructive testing

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The goal of this program is to develop an automated, optical inspection station useful on a spectrum of munition related components.

Laser scatter is composed of speckle whose exact distribution cannot be predicted. However, its envelope can be used to typify the surface profile. Thus, the ability to detect surface features is a function of the ability to resolve this envelope which, in turn, is a function of the number of speckle per unit solid angle in the scatter plane. Since the dimensions of speckle are inversely proportional to the illuminating laser beam diameter, there is

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an implicit lower bound to features detectable by this method. Also, there are lower limits imposed on defect detectability, for actual production items, from background noise arising from surface variations due to the machining process employed. Both speckle and surface variances must be statistically computed on a per component basis in order to establish the usefulness of scatter inspection for that particular component.

In order to be applicable to a wide spectrum of situations, a generalized scatter sampling system was constructed. The output is fed into a logic board, providing a degree of pattern recognition capability and yielding a system adaptable to the more difficult discrimination problems.

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FIGURES

INTRODUCTION

Figure 1 illustrates the basic concept behind using laser beam scatter in examining surfaces for structural defects. A laser beam is focused onto the surface of interest and scattered into space. This scattered distribution of light can be observed by placing a viewing screen to intercept the light, as shown. Because the geometry of this scatter is characteristic of the laser illuminated surface, basic information on the surface structure may be obtained from an analysis of the scatter distribution. In that surface anomalies, such as cracks or pits, will significantly alter the scatter profile, it is believed that an electro-optical system may be constructed to monitor this profile that will automatically signal the presence of defective components.

The advantages provided by such an optical scatter inspection system would include non-contact inspection, high feed-through rates and high sensitivity. This system would serve to replace the human for visual inspection and greatly reduce the accompanying error rate.

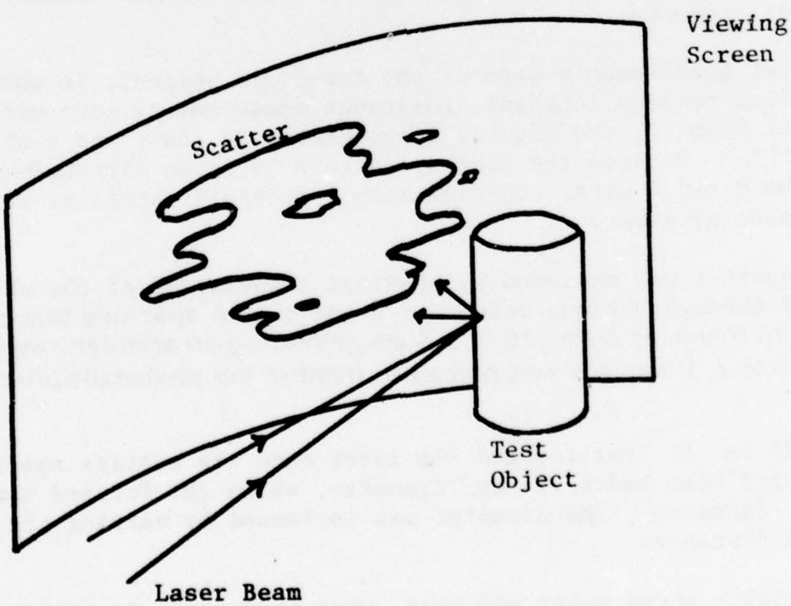


Fig. 1
Laser Scatter

EXPERIMENTAL SET-UP

The initial phase of development for an automatic defect detection system was to conduct experimental measurements dedicated to determining the nature of laser scatter and how it is affected by structural variations.

The system used in the experimental portion of this program is outlined in Fig. 2. In this set-up, a laser beam is focused onto the surface of a prepared specimen and the resultant scatter is monitored as a function of the surface detail by a photomultiplier system.

The finishes used on the 5 x 5 cm sample blocks were prepared by polishing with various grade grits.

The laser beam came from a 1 milliwatt, Spectra Physics Model 133 Laser. The monitoring photomultiplier system, an EG&G Model 585-60 series high sensitivity detection head, was placed 63mm from the scattering surface. At this distance, measurements were well within the far field scatter pattern. The laser beam was placed as to strike from an angle of -10° from the perpendicular to the specimen's surface. The $+ 10^{\circ}$ angle provided the zero reference for angular scatter intensity measurements.

In that measurements were of the far-field pattern, in which the luminous flux remains constant, luminance measurements were made as a function of θ and ϕ, the angular displacement in the y and z planes, respectively. Because the scatter pattern is often asymmetrical between the θ and ϕ axes, two-dimensional intensity profiles were obtained when necessary.

The scatter was measured by physical translation of the photomultiplier through various values of θ and ϕ. An aperture that could be varied in diameter from .16 to 2.5 cm providing an angular resolution of from .15 to 2.3 degrees was placed in front of the photomultiplier.

A 1.25 cm fl lens focused the laser onto the surface specimen. The unfocused beam had a .11 cm diameter, while the focused beam had a .002 cm diameter. The diameter was increased by varying the lens-to-surface distance.

A variable speed motor was used, when necessary, to rotate the sample plate under the laser beam. By careful alignment of the sample to assure that the illuminated surface corresponded exactly to the axis of rotation, the same spot diameter and position could be held on the

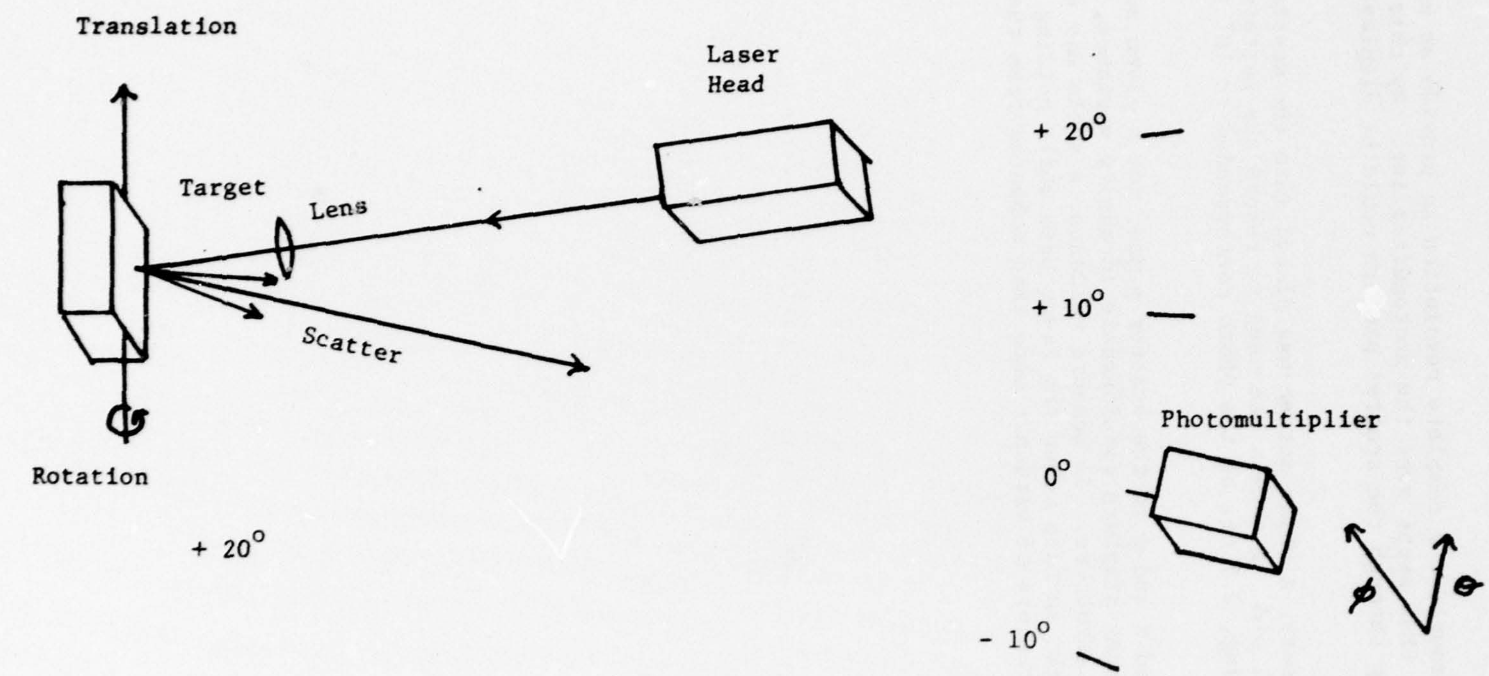


Fig. 2

Set-up For Scatter Measurements

sample block throughout a complete revolution to provide an unchanging scatter pattern that swept over the photomultiplier. By this means, a complete sweep through the scatter pattern could be displayed on an oscilloscope.

When necessary, a white screen was placed into the scatter pattern as a visual aid. A camera was used to record the pattern. By proper positioning, 2.5 cm. on the photo corresponded to 16° in the scatter plane.

At any fixed θ and ϕ in the scatter plane, for a given surface finish, the scatter displays considerable intensity variance, depending on its fine structure. To measure variance, a table was set to translate the test surface under the laser beam while holding θ and ϕ fixed. Measurements of variance were than computed from the photomultiplier data.

DISCUSSION OF RESULTS

The scatter geometry may be accounted for by using a combination of geometric and interferometric considerations. In all cases the scatter pattern is composed of speckle. Speckle gives the scatter the appearance of being composed of numerous spots of light and arises from interference between laser radiation scattered from adjacent regions across the illuminated surface. The distribution of speckle size is proportional to λ/d, where λ is the wavelength of the laser and d is the width of the laser spot striking the surface. As the spot diameter diminishes, the speckle size increases appreciably, until the speckle, for very small laser spots, becomes the dominant scatter component. For large laser beam diameters, where speckle is minute relative to the active area of the photodetector, the scatter distribution may be accounted for by using geometric considerations. As the speckle becomes the dominant component, only the general distribution may be predicted through geometric considerations, with the fine structure, contributed by speckle, varying unpredictably due to microscopic variations found in surface detail across any production item.

An example of the sensitivity of laser scatter to minute surface deviations is illustrated in Fig. 3.

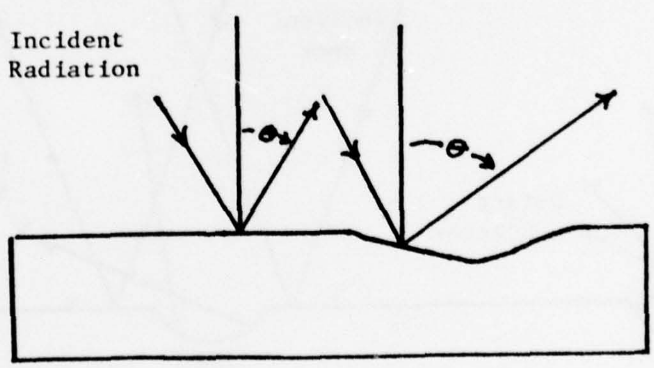
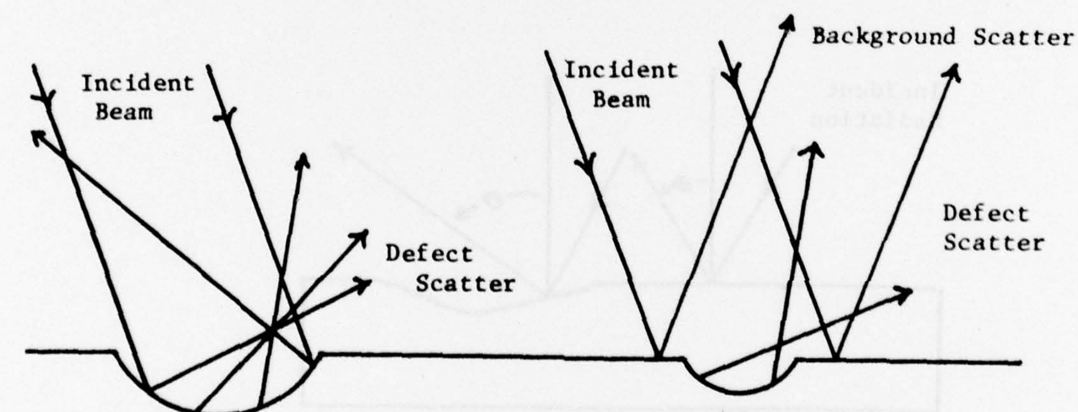


Fig. 3
Scatter Direction Variation

For this case, using a large beam diameter, the expected scatter can be handled by using the relationship that the angle of incidence equals the angle of reflection. As the beam is scanned along the item's surface and reaches a variation in profile large in comparison to the beam diameter, the angular deviation of the surface will cause twice the angular deviation of the scattered beam. Because of the large leverage arm, the displacement is greatly exaggerated in the scatter plane. At a distance of 25 cm from the scattering surface, a 1° deviation in surface profile will result in a displacement of .425 cm in the reflected beam. Assuming a beam spread of 3 milliradians, it should be possible to detect changes in surface profile of 0.4 degrees.

This example assumes that the surface variation is large with respect to the focused beam. As the defect approaches the beam dimension, the scatter pattern will spread in a manner that can be computed using the same geometric relationship. For example, a dent will act as if it were a concave mirror, producing a large spread in the angular scatter (Fig. 4A). As the dent's width decreases below that of the beam, the scatter will become diminished in intensity, as it now intercepts a lesser portion of the incident radiation. The defect scatter must now be discriminated against a field of this background scatter. The limit on sensitivity for minor defects is now imposed by the ability to discriminate between the two components (Fig. 4B).



(A)

Defect Larger Than Laser Beam

(B)

Defect Smaller Than Laser Beam

Fig. 4
Laser Versus Defect Size

SURFACE FINISH

The preceding considerations hold for specimens displaying mirror finishes. However, almost all production items display finishes that are far from ideal. Most surfaces will spread the scatter into a distribution falling somewhere between specular and the cosine distribution associated with complete diffusivity. (Fig. 5)

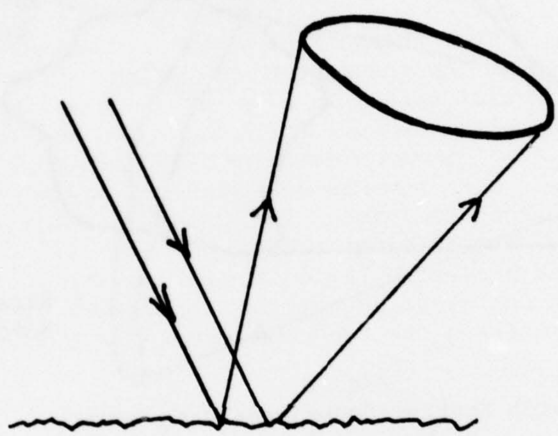


Fig. 5

Scatter From A Diffuse Surface

This diffusivity causes a degradation in sensitivity to variations in surface profile. For example, sensitivity to gradient variations depends on the minimum angular shift discernable in the scatter direction, diffusivity leads to an inexact location of scatter, thus a loss in resolution. Also, a diffuse scatter presents a more wide-spread background against which defect scatter must be discriminated. For example, consider the effect of a scratch on the scatter pattern. (Fig. 6) Optically, the scratch would be expected to affect the scatter as if it were a cylindrical concave mirror, that is, it will scatter light in a linear configuration perpendicular to the axis of the scratch. If the scratch width is lesser in extent than the focused laser beam, the scatter will consist of the scratch scatter profile superimposed on the diffuse background scatter. As the scratch diminishes in size, it intercepts less light, until a limit is reached at which point its scatter can no longer be discriminated; thus surface finish limits sensitivity to defects.

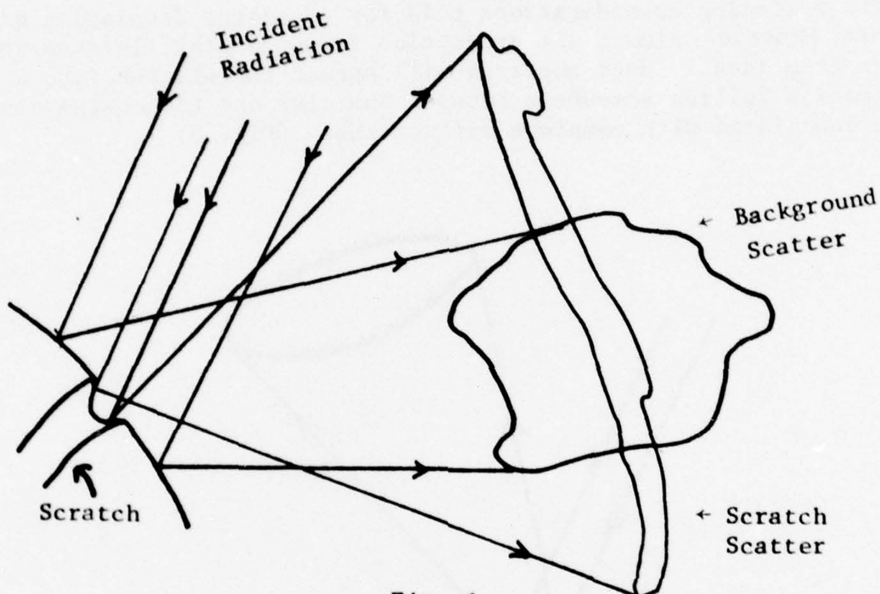


Fig. 6
Scratch Scatter Superimposed on Normal Background Scatter

SPECKLE

It would appear from preceding considerations that, in order to increase defect sensitivity, one merely has to decrease the diameter of the laser beam to match the dimension of the defect, the limitation then being the minimum theoretical spot attainable and the ability to hold the scanned surface within the focus of this spot. Unfortunately, at smaller spot diameters, speckle becomes the major component of scatter. (Fig. 7)

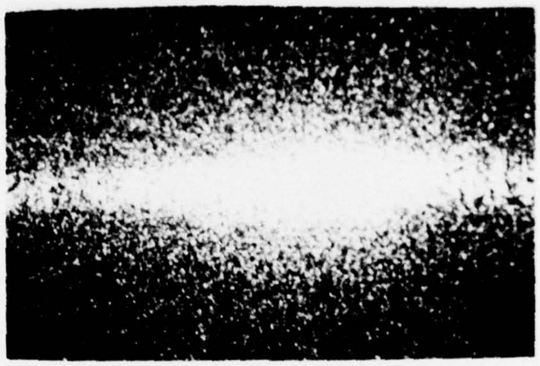


Fig. 7
Photo Illustrating Speckle
Composition of Scatter

The highest spatial frequency component of speckle is limited by the relationship $f = d/\ell\lambda$, where f is the spatial frequency, d is the laser spot diameter, λ is the laser wave length, and ℓ is the surface-to-scatter plane distance. On visual observation, the scatter has the appearance of being composed of much larger speckle than implied by the formula. This is because the relationship sets the upper bond for spatial frequencies in the scatter, while the exact frequency distribution is a function of both the laser spot diameter and the surface texture. Because both the defect and background surface have surface texture, smaller defect detection may become a problem of discriminating defect speckle from surface finish speckle.

The variance obtained in directly measuring the scatter intensity using a photodetector at any given point in the scatter plane is proportional to N, N being the number of speckle included in the measure. To maintain the same precision in measuring the scatter envelope, one must increase the area of the photodetector. However, this compromises the spatial resolution of the scatter geometry.

It becomes obvious that a minimum exists for the sizes of defects detectable at the point where the increased sensitivity, arising from using smaller beam diameters, is offset by the loss in scatter spatial resolution, imposed by the accompanying increased speckle dimensions.

BACKGROUND NOISE

The discrimination of defects in production items by use of laser scatter becomes a complex problem subject to many variables. The basic premise is that, as the surface of the test object is being systematically scanned by the laser, there will be a detectable variation in the scatter geometry as a defect is passed over.

Consider a beam passing over a scratch. If the focused laser beam is lesser in diameter than the scratch width, all the incident radiation will fall into the concavity of the scratch, and the scatter pattern will change abruptly from that typifying a good surface to that of a scratch, and electronic discrimination of this change can be relatively straight-forward. As a defect diminishes in size relative to the beam, the beam overlaps the defect, and the scatter pattern consists of, simultaneously, components from both the defects and the normal background. The problem becomes one of recognizing the defect componant from that of the background. As the defect is further reduced relative to the incident beam, a point is reached where the defect scatter is hopelessly lost in the background noise.

In addition to the previously mentioned factors affecting sensitivity, one runs into surface variations that do not affect component quality, yet produce significant variations in scatter. The variations can be caused by waviness, dents, dimensional variations, machine marks, etc. The difficulty is that these may produce the same effect on scatter as defects, only lesser in magnitude. In fact, many can be considered as being defects of insignificant dimension. For example, minor dents are considered acceptable, while major dents are cause for rejection. Alternatively, the polish of an item is composed of numerous, fine scratches, while large scratches are unacceptable. Thus, we find that as defects diminish in magnitude, their scatter profile blends more and more into the random background scatter.

In using laser scatter inspection techniques on any given production component, it would be expected that a lower limit would be imposed on detectable defects due to background fluctuations. (Fig. 8)

Because surface and defect characteristics vary so widely between munitions components, depending on the metals and machining process employed, a numerical description of finish will not provide a measure of the threshold of defect detection and for any given component the limits of detectability must be statistically established. The final problem becomes one of defining at what point defects become so trivial as to be considered part of background noise.

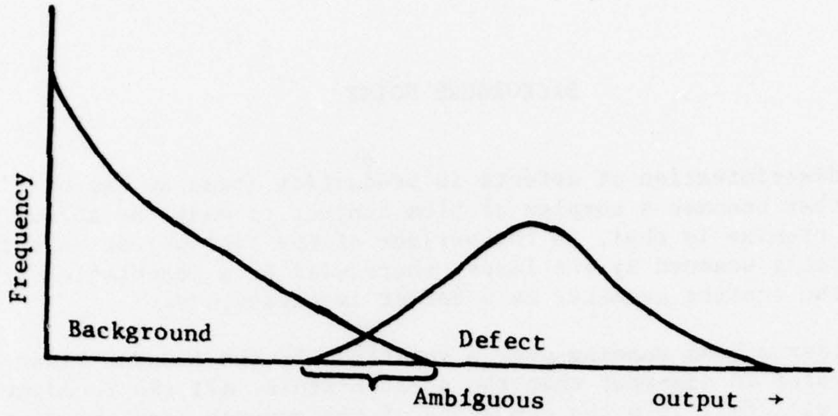


Fig. 8
Statistical Crack/ Background Discrimination

The surface of a production item can have a finish that varies anywhere from optically smooth to perfectly diffuse. If the surface is optically smooth, any scatter can be interpreted as a defect; if diffuse, a change in scatter geometry will have to be interpreted to signal the presence of a defect. As the laser beam is scanned across a surface, regions of varying diffusivity are encountered, causing a statistical variance in beam spread that must be accounted for in a working inspection system.

In most machining operations, such as milling, turning, or polishing, the cutting processes tend to produce linearly oriented machine marks (Fig.9). These machine marks produce scatter similar to scratches, and hence, resolution of linear defects oriented parallel to the machine marks is significantly reduced.

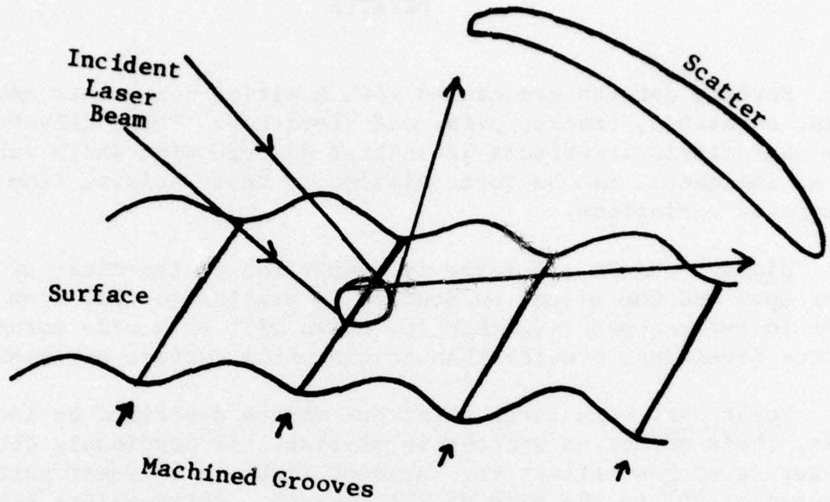


Fig. 9
Typical Machined Surface

DEFECTS

Surface defects associated with munition components can include nicks, scratches, cracks, pits, and blemishes. These defects each have characteristic effects on scatter distribution which unfortunately, as indicated, can be quite similar to those arising from normal background variations.

Nicks. - Nicks are large in comparison to the diameter of the laser spot and the effect on scatter is similar to that from a sharp shift in surface profile, that is, there will be a wide swing in scatter direction, greater than arising from surface waviness.

Scratches. - As large scratches may be described as long, narrow nicks, their effect on scatter is similar. As previously described, smaller scratches reflect the incident light in a linear pattern, oriented at 90° to the axis of the scratch. Intermediate scratches produce a blending of the two effects.

Because on many production items the normal background scatter is linearly oriented to monitor for unusual surface scratches, one has to monitor for variations in either scatter orientation or extent. Sensitivity to scratches lying parallel to the machining marks will be compromised.

Fortunately, smaller scratches will have little effect on the structural integrity of the component.

Cracks. - Perhaps the most serious of the defects. The effect of cracks on scatter can be that of either nicks or scratches, depending on the width of the crack relative to the laser spot. In fact the same crack may display both effects as the laser is scanned down its length. In addition, there is a trapping effect so that overall scatter intensity will diminish. (Fig. 10) Tight cracks may display very small widths and be almost impossible to detect. In using smaller laser beam diameters, the problem may become more one of detecting variations in speckle distributions than detecting variations in scatter geometry.

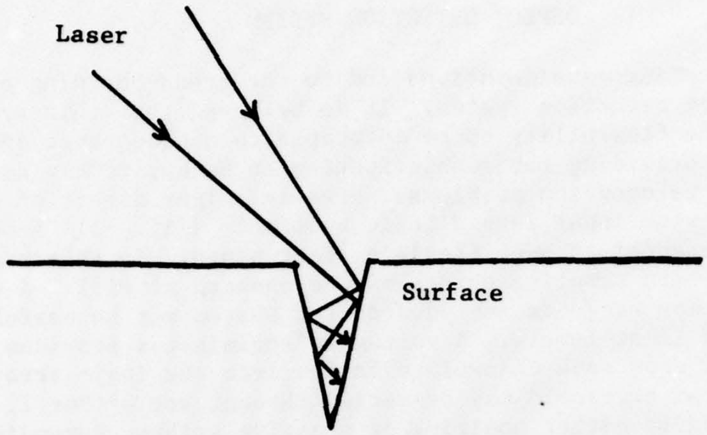


Fig. 10
Light Trapping By Crack

Pits. - Pits will act as little concavities on the surface, increasing the scatter spread.

Blemishes. - Blemishes usually have a different texture than the background and usually spread the scatter into more of a cosine distribution. Also there is often a difference in absorption, reducing the total radiation scattered.

DEFECT DETECTION SYSTEM

The preceding considerations led to the bread-boarding of a versatile defect detection system. It is believed that this system will provide the flexibility to be adaptable to a wide range of components, while providing the sophistication to be applicable to the more difficult recognition problems. Parallel light detection circuits are used to provide input into a logic section. (Fig. 11) Input is fed into each channel through flexible light pipes. In this manner, the scatter pattern sampling points may be changed at will. A variable amplification stage is included so the system may be useful over a wide range of light levels. A voltage discriminator provides an on - off output from each channel to be fed into the logic array. The discriminator threshold may be varied through use of Pot 2, and may be triggered by either positive or negative spikes, depending on the position of switch 2. The discriminator outputs are fed into the logic board (Fig. 12) which may be programmed to discern if the scatter sample has the geometry characteristic of a defect. Banana plug connectors are used to provide programming flexibility. Each stage of the logic indicates its requirements are met by turning on a photodiode; thus the degree of fit for the sampled scatter profile to the defect profile is directly observable. Any surface anomaly passing the final stage is deemed a defect, and the output can be used to switch on a reject mechanism.

For example, assume a crack is the defect being sought. One would be monitoring for a change in scatter from a cosine distribution to a linear configuration (Fig. 6). For this case, one could reasonably anticipate an increase in output from two opposed light pipes (Fig. 13 A & D) with a decrease in the remainder (B,C,E,F,G).

Depending on the crack orientation, the logic would monitor for increased output from two opposed light pipes, with simultaneous decreased outputs from the remainder to signal a defect.

The schematic for each stage in the optical processing chain is shown in Fig. 14.

Two types of laser scanning systems were also constructed to scan a wide range of production items. The first consists of an x, y translator, and will scan flat objects, while the second consists of a variable speed motor and a linear translator to provide a helical scan of cylindrical objects.

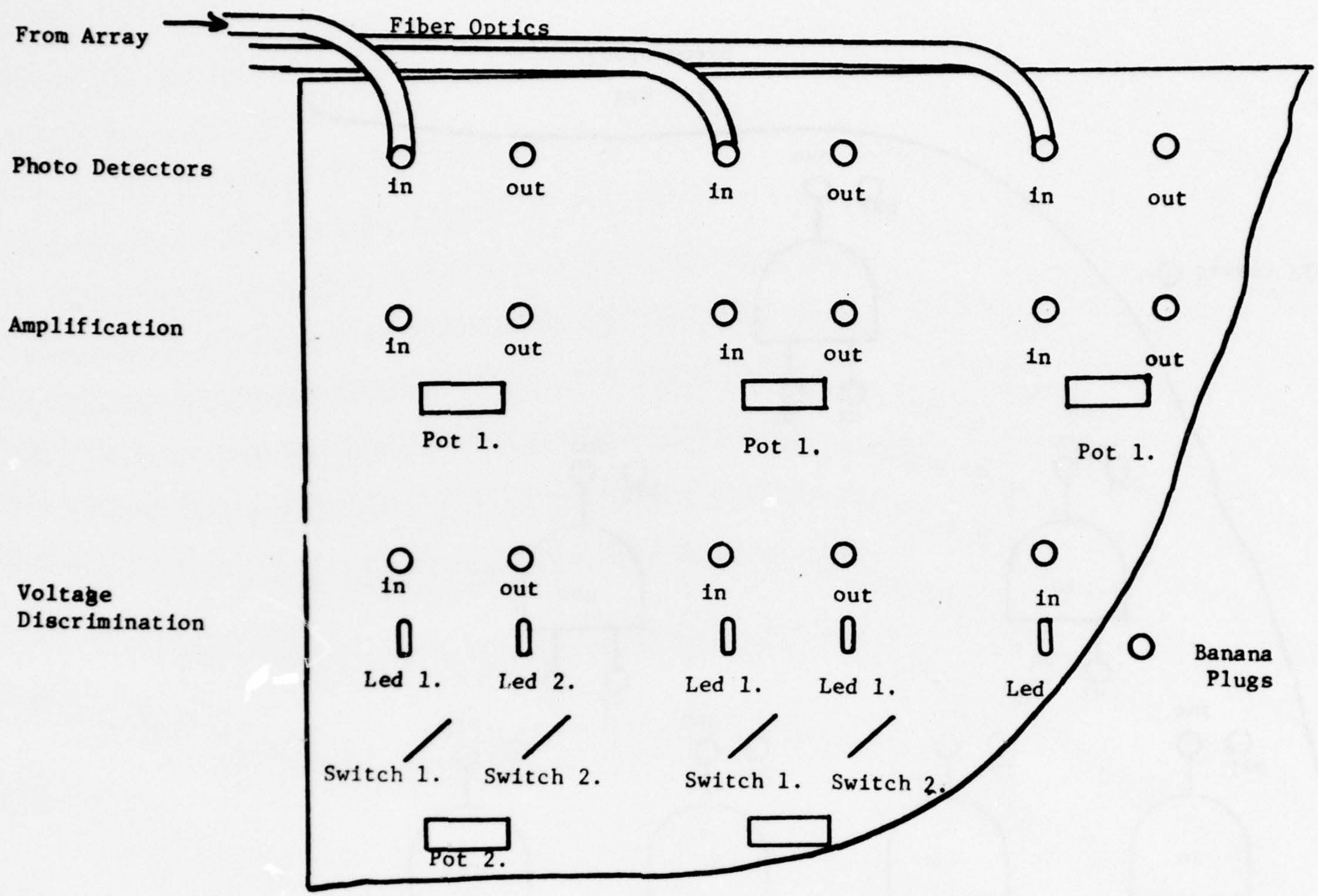


Fig. 11.
Photodetector, Discriminator Board

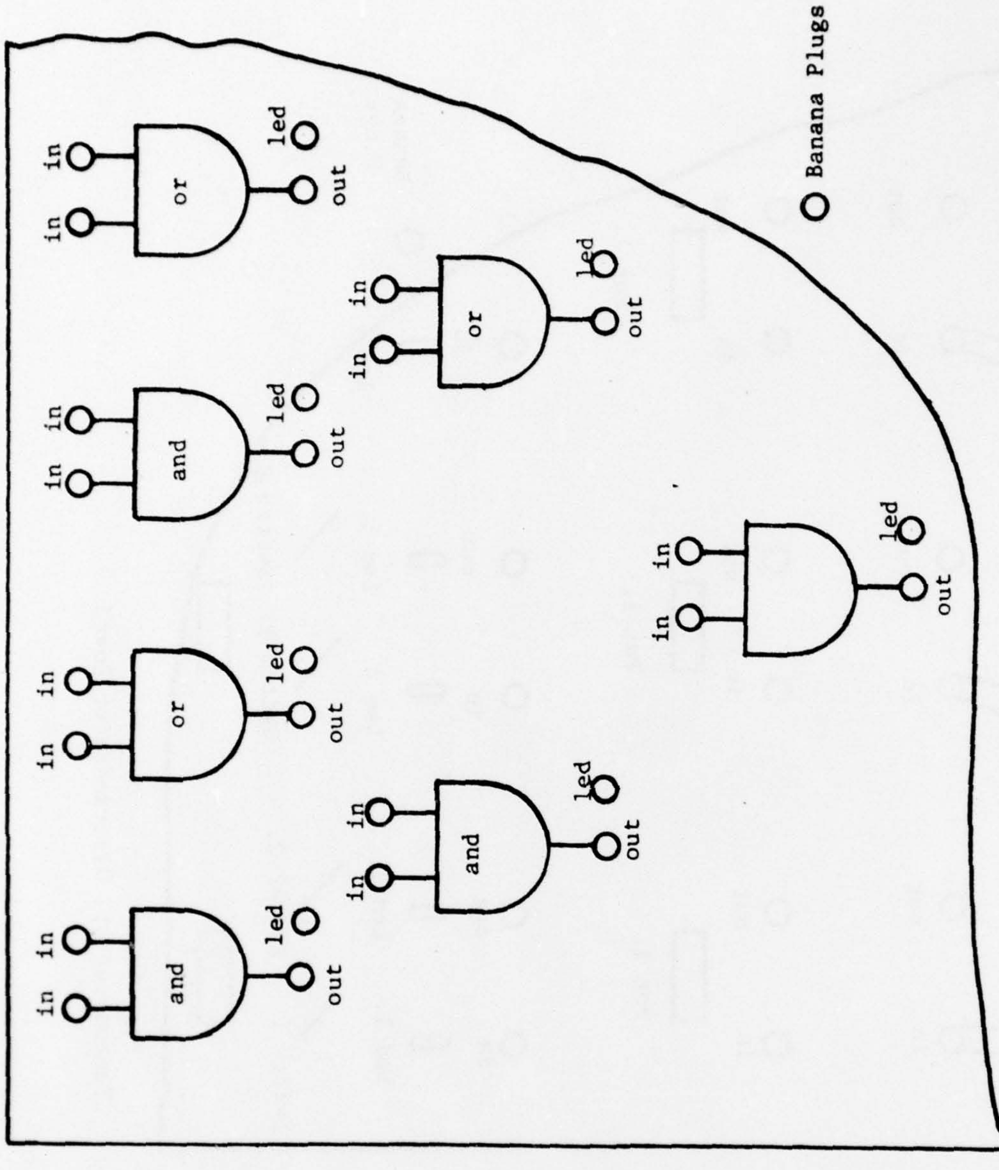


Fig. 12
Logic Board

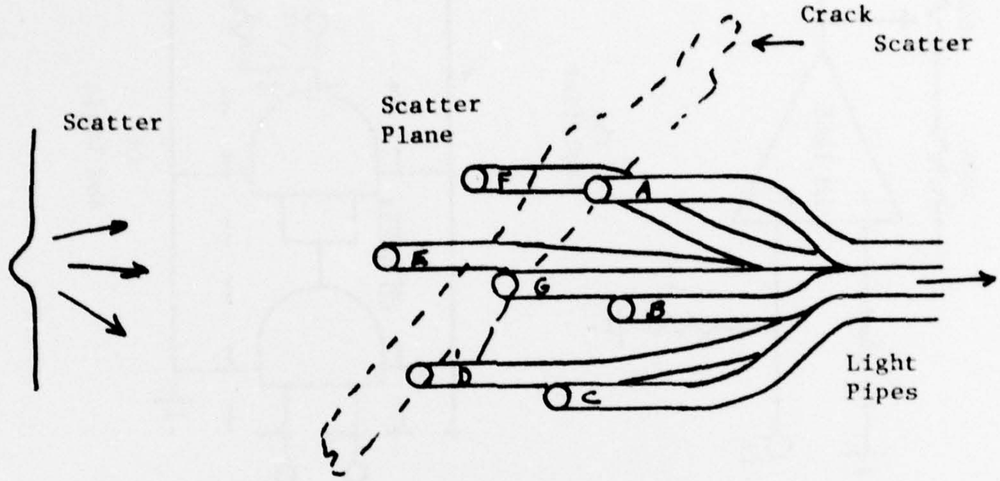
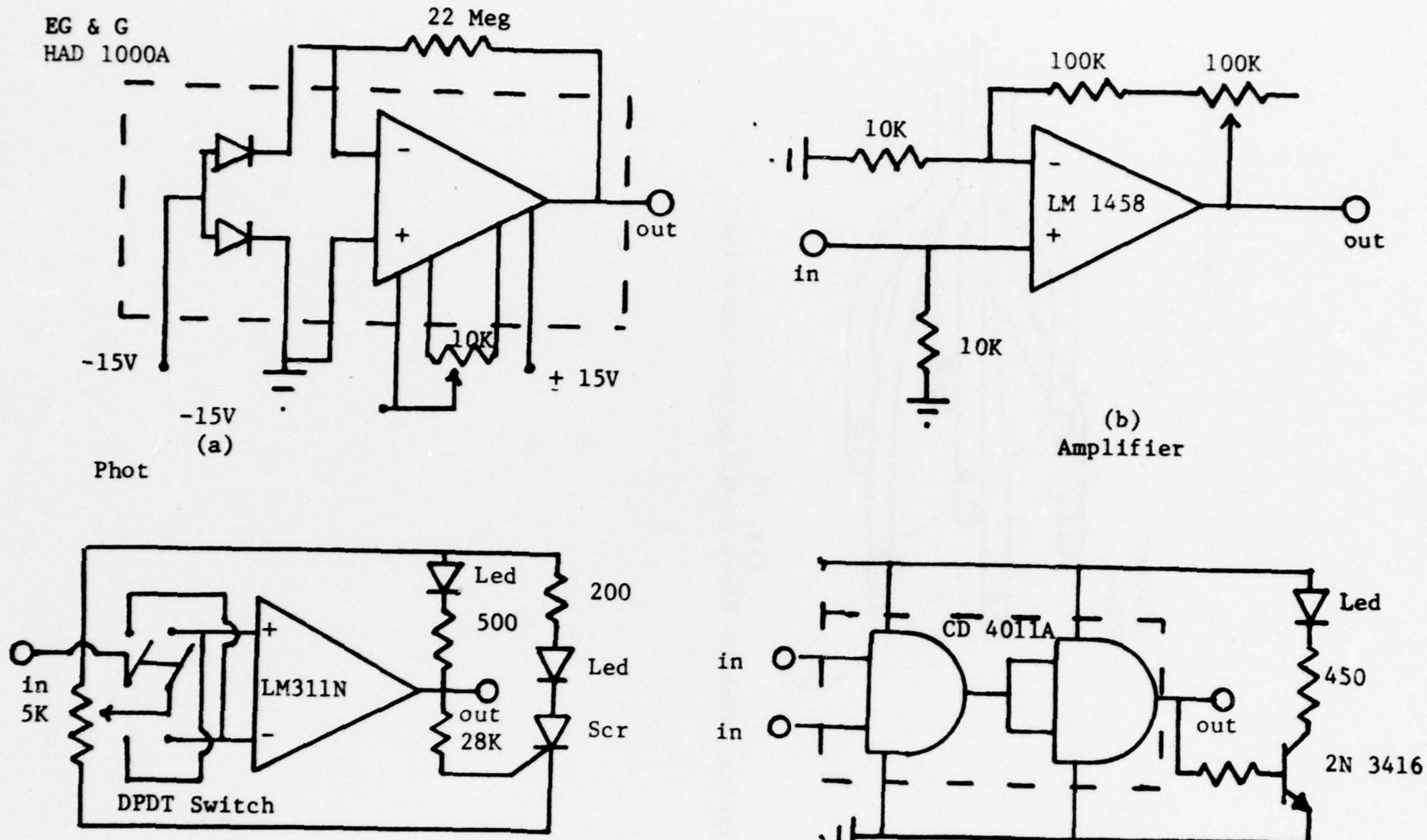


Fig. 13
Typical Scatter Plane Sampling Configuration



(c)
Voltage Discriminator

Fig. 14
Schematic

(d)
And Logic

CONCLUSIONS

The initial phases of analysis and development of a working, optical inspection station have been covered and a versatile pilot automatic scatter analysis system has been bread-boarded that displays potential to be useful for a wide variety of optical inspection problems. Future work will include refining this inspection system and will key in on several problem areas where there exists a need for automatic optical inspection and specifically adapt the system to the more promising of these areas.

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